ADA278957

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
ATC-216	DOT/FAA/RD-94/12	

4. Title and Subtitle	5. Report Date / 6. Performing Organization Code
Terminal Doppler Weather Radar (TDWR) Low Level Wind Shear Alert System 3 (LLWAS 3) Integration Studies at Orlando International Airport in 1991 and 1992	5. Report Date: 20 April 1994 6. Performing Organization Code:
7. Author(s): Rodney E. Cole and Russell F. Todd	8. Performing Organization Report No.: ATC-216
9. Performing Organization Name and Address: Lincoln Laboratory, MIT P.O. Box 73 Lexington, MA 02173-9108	10. Work Unit No. (TRAIS) 11. Contract or Grant No.: DTFA01-93-Z-02012
12. Sponsoring Agency Name and Address: Department of Transportation Federal Aviation Administration Washington, DC 20591	13. Type of Report and Period Covered: Project Report 14. Sponsoring Agency Code

15. Supplementary Notes

This report is based on studies performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology. The work was sponsored by the Air Force under Contract F19628-90-C-0002.

16. Abstract

In 1993 the Federal Aviation Administration (FAA) began deploying two new wind shear detection systems: the Terminal Doppler Weather Radar (TDWR) and the third-generation Low Level Windshear Alert System (LLWAS 3). Currently, 9 airports are scheduled to receive both a TDWR and an LLWAS 3. This number may eventually increase to as high as 45. When co-located the systems will be integrated to provide a single set of wind shear alerts and improve system performance.

The TDWR production schedule required one of three integration algorithms to be chosen for specification by fall 1991. The three algorithms are the prototype integration algorithm developed at the National Center for Atmospheric Research (NCAR) and the two algorithms developed at MIT Lincoln Laboratory (MIT LL). To assess the performance of the three algorithms, MIT LL performed a study of integration, TDWR, and LLWAS 3 algorithms at Orlando International Airport (MCO) in the summer of 1991. Based on the results of this study, MIT LL and NCAR issued a joint recommendation that the FAA procure one of the integration algorithms developed at MIT LL. This algorithm was demonstrated at the Orlando International Airport in the summer of 1992.

Results of the 1991 comparative study and a followup study of the TDWR, LLWAS 3, and Message Level integration algorithms at Orlando in 1992 are discussed. All the algorithms met the requirement of detecting 90 percent of microburst level wind shear with loss events. LLWAS 3, Build 5 TDWR, and the MIT LL integration algorithms with Build 5 TDWR all met the requirement that less than 10 percent of wind shear alerts be false. The NCAR prototype did not utilize Build 5 TDWR. Build 4 TDWR and all integration algorithms run with Build 4 TDWR did not meet the false-alert requirement. Detailed descriptions of the algorithms are given. The methodology for estimating various algorithm performance statistics based on a comparison with a dual-Doppler algorithm is detailed.

17. Key Words		18. Distribution Statement
TDWR LLWAS 3 integration	microburst wind shear algorithm	This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	66	

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ABSTRACT

In 1993 the Federal Aviation Administration (FAA) began deploying two new wind shear detection systems: the Terminal Doppler Weather Radar (TDWR) and the third-generation Low Level Windshear Alert System (LLWAS 3). Currently, nine airports are scheduled to receive both a TDWR and an LLWAS 3. This number may eventually increase to as high as 45. When co-located, the systems will be integrated to provide a single set of wind shear alerts and improve system performance.

The TDWR production schedule required one of three integration algorithms to be chosen for specification by fall 1991. The three algorithms are the prototype integration algorithm developed at the National Center for Atmospheric Research (NCAR) and two algorithms developed at MIT Lincoln Laboratory (MIT/LL). To assess the performance of the three algorithms, MIT/LL performed a study of the integration, TDWR, and LLWAS 3 algorithms at Orlando International Airport (MCO) in the Summer of 1991. Based on the results of this study, Lincoln Laboratory and NCAR issued a joint recommendation that the FAA procure one of the integration algorithms developed at MIT/LL. This algorithm was demonstrated at the Orlando International Airport in the summer of 1992.

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ACKNOWLEDGMENTS

We would like to thank Larry Cornman, Dave Albo, and William Mahoney of NCAR/RAP for the use of the prototype integration software and for their help in installing this software in our system. We would like to thank Skip Copeland and all of the site personnel for their extremely hard work in finding sites for the mesonet, and for installing and maintaining the mesonet stations. We would like to thank Ann Cope and Don McLaughlin for the very long hours required to put together the software for the Lincoln algorithms, and the numerous other software engineers that pitched in to help when time became short. Lastly, we would like to thank Wes Wilson for his support of this project.

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1. INTRODUCTION

In 1993 the Federal Aviation Administration (FAA) began deploying two new wind shear detection systems: the Terminal Doppler Weather Radar (TDWR) [6] and the third–generation, Low Level Windshear Alert System (LLWAS 3) [8]. Currently nine airports are scheduled to receive both a TDWR and an LLWAS 3. This number may eventually increase to as high as 45. When co–located, the systems will be integrated to provide a single set of wind shear alerts and improve system performance.

The TDWR production schedule required one of three integration algorithms to be chosen for specification by fall 1991. The three algorithms are the prototype integration algorithm developed at the National Center for Atmospheric Research (NCAR) [5] and two algorithms developed at MIT Lincoln Laboratory (MIT/LL). To assess the performance of the three algorithms, MIT/LL performed a study of the integration, TDWR, and LLWAS 3 algorithms at Orlando International Airport (MCO) in the summer of 1991. Based on the results of this study, Lincoln Laboratory and NCAR issued a joint recommendation that the FAA procure one of the integration algorithms developed at MIT/LL. This algorithm was demonstrated at the Orlando International Airport in the summer of 1992.

This report presents the results of the 1991 comparative study and a follow–up study of the TDWR, LLWAS 3, and Message Level integration algorithms on 1992 data collected at MCO. Detailed descriptions of the algorithms are given, followed by a section on data collection at the Orlando testbed. Next, the methodology for estimating various algorithm performance statistics based on a comparison with a dual–Doppler algorithm is detailed. Lastly, the results of applying this methodology to the various algorithms are presented and discussed for data sets collected during 1991 and 1992. Results of a study on the real–time operational impact of TDWR, LLWAS 3, and Message Level integration in 1992 at MCO are presented in Appendix A.

The results presented concern only the detection of wind shear with a loss of head wind, considered the primary aviation wind shear hazard. While important, the ability to detect wind shear with a gain of head wind was not a determining factor in the comparison since each integration algorithm uses the same logic to issue gain alerts.

2. ALGORITHM DESCRIPTIONS

This study analyzes the performance of six algorithms: the three candidate integration algorithms, TDWR and LLWAS 3 as stand–alone systems, and a fourth integration algorithm included to aid the comparison. Each algorithm produces a set of alphanumeric runway alerts. Each concrete runway is associated with four operational runways, two for arrivals and two for departures, and each is issued a separate alert. Each alert contains an alert type, an intensity estimate, and a location of first encounter.

The alert types are:

- Microburst Alert (MBA), a wind shear with a loss of head wind of 30 knots or greater and
- Wind Shear Alert (WSA), a wind shear with a loss of head wind of at least 15 knots and less than 30 knots, or a gain of head wind of 15 knots or greater.

The intensity is the loss or gain in head wind that an aircraft flying along the flight path is expected to experience, rounded to the nearest 5 knots.

The location of first encounter is the location on the flight path where an aircraft is expected to first encounter the wind shear event. The location of first encounter is given as on–the–runway, 1 mile, 2 miles, or 3 miles from runway threshold. The maximum alert location is 2 miles for departure runways and 3 miles for arrival runways.

The integration algorithms are of two types: message level and product level. Message level algorithms integrate the alpha–numeric runway alert messages. Product level algorithms integrate intermediate algorithm products such as TDWR microburst shapes, TDWR features aloft [2], and LLWAS divergence values. The integrated products are used to generate the alphanumeric alerts.

The four integration algorithms are:

- Prototype Product Level (PL–A),
- Product Level (PL–B),
- Message Level (ML), and
- Union (UN).

The integration algorithms vary significantly in the logic used to generate loss alerts, and the logic employed by each is discussed in detail below. All of the integration algorithms issue wind shear alerts with a gain of head wind using the same logic. LLWAS provides the wind shear with gain alerts inside its coverage region and TDWR provides them outside of this region.

2.1. TDWR

TDWR detects wind shear by analyzing Doppler radar returns from an area covering the airport. Two versions of the TDWR microburst algorithm were used to generate alerts for this study. The

first is the algorithm used in the initial TDWR deployment (Build 4), and the second is an upgrade to the first deployment (Build 5b). The Build 5 algorithm includes *flight path shear integration* to sharpen the accuracy of the intensity estimates. The TDWR deployed with LLWAS 3 systems uses flight path shear integration. The non–shear–integration method is included in this study because the PL–A algorithm software did not use flight path shear integration.

The TDWR microburst detection algorithm uses four processing steps:

1. Build loss segments by examining each radial of Doppler data for segments of diverging radial velocities.
2. Group loss segments.
3. Fit microburst shapes to groups of loss segments.
4. Intersect microburst shapes with runway corridors to determine runway location and loss estimate.

Without flight path shear integration the loss estimate for a given runway is the maximum loss estimate of any microburst shape that intersects its runway corridor. When flight path shear integration is used, the loss estimate is computed by integrating a fractional loss from each microburst shape along the runway corridor. This fractional loss is an estimate of the fraction of the maximum loss from each microburst shape that an aircraft may experience.

In addition to detecting diverging radial velocities, TDWR also detects weather features aloft that are associated with microburst activity. These features include both Doppler signatures, such as converging winds aloft, and reflectivity signatures, such as descending storm cores. These features are used to reduce the time that it takes to issue an alert. If these features are not present, the microburst algorithm requires a detection on two successive radar scans before issuing an alert. If sufficient features aloft are present, the alert is issued with the first detection of wind shear. Features aloft play an important role in the product level integration algorithms.

2.2. LLWAS 3

LLWAS 3 detects wind shear by analyzing wind data gathered from a network of anemometers surrounding the airport runways. Divergences and convergences in the surface wind field are estimated from the wind data from triples and pairs of anemometers. Divergence values are used to generate loss alerts and convergence values are used to generate gain alerts. Detections of wind field divergence and convergence are tested for statistical significance before they are used to issue an alert. If a statistically significant divergence is sufficiently large, the determination is made that a microburst has been detected. Due to the anemometer network spacing, it is likely that the measured winds do not reflect the maximum outflow strength. Using a symmetry hypothesis and knowledge of the network geometry, a statistically based correction factor is applied to reduce the effect of under measurement. If the divergence is not sufficiently large or if the detection is a convergence, no correction factor is applied. In either case, the issued alert is a directly–measured wind shear along the direction of each runway.

2.3. Product Level–A (PL–A)

The PL–A algorithm is the prototype product level integration algorithm developed at NCAR. This algorithm attempts to reduce the number of false wind shear level loss alerts by dropping weak wind shear level LLWAS loss detections that are not near additional indications of hazardous weather (strong TDWR or LLWAS loss detections or TDWR features aloft). After possibly dropping weak wind shear level LLWAS loss detections, the algorithm issues the strongest alert generated from either LLWAS or TDWR for each operational runway. If one system is generating a loss alert and the other is generating a gain alert, the loss alert is issued. A prototype of this algorithm was installed and operated at Stapleton International Airport in Denver from 1988 to 1991.

The logic used by PL–A to convert LLWAS wind field divergence values into runway alerts differs from the logic used in LLWAS 3. PL–A scales the divergence values into loss estimates and maps them to a regular grid. Next, it fits TDWR style microburst shapes to the gridded loss estimates. Alerts are then generated by intersecting the shapes with the runway corridors using Build 4 TDWR logic.

2.4. Product Level–B (PL–B)

The PL–B algorithm is a product level algorithm developed at MIT Lincoln Laboratory. This algorithm is similar to PL–A, but uses streamlined processing, and attempts to reduce a greater number of false wind shear alerts as well as false microburst alerts from both LLWAS and TDWR. Unlike PL–A, this algorithm very closely follows the LLWAS 3 logic for converting wind field divergence values into runway alerts. Like the PL–A algorithm, PL–B drops weak wind shear alerts from LLWAS that are not near additional indications of hazardous weather. Weak wind shear alerts from TDWR are treated in the same manner. Additionally, weak microburst alerts, typically alerts with a 30 knot loss estimate, that are not near indications of hazardous weather are reduced to 25 knot wind shear alerts. This removes a microburst alert that is likely to be false, but still gives an indication to the pilot that some level of wind shear may be present in case the alert was not false. TDWR alerts for events lying outside the region of solid LLWAS detection coverage are not subject to the verification and modification process.

Algorithm thresholds are set for individual runways. This is important since some runways have better LLWAS or TDWR coverage than others. When the two systems issue conflicting alert types, gain vs. loss arbitration logic is applied to determine which alert to issue. When the two systems are issuing loss alerts, the strongest alert is issued, and when both are issuing a gain alert, the LLWAS alert is issued since LLWAS has been demonstrated to issue more credible gain alerts than TDWR. The details of the alert arbitration are given below in the section on the Message Level algorithm.

2.5. Message Level (ML)

The ML algorithm is a message level algorithm developed at MIT Lincoln Laboratory [3]. This algorithm attempts to reduce false wind shear and microburst level alerts from both TDWR and

LLWAS 3 in much the same way that PL–B does. Since this is a message level algorithm the only indications of hazardous weather are the TDWR and LLWAS runway alerts. Alerts from the two systems are compared on a runway–by–runway basis. Weak wind shear level alerts given by only one system are dropped, and weak microburst alerts given by only one system are reduced to wind shear level. Unlike the product level algorithms, when both systems are issuing a loss alert the integrated loss estimate is based on an averaging technique to sharpen the estimated loss. When the two systems issue conflicting alert types, gain vs. loss arbitration logic is applied to determine which alert to issue. When both are issuing a gain alert, the LLWAS alert is issued, since LLWAS has been demonstrated to issue more credible gain alerts than TDWR. TDWR alerts for events lying outside the region of solid LLWAS detection coverage are not subject to the verification and modification process. The parameters that control the logic to reduce false alerts, sharpen loss estimates, and arbitrate between loss and gain alerts are discussed in detail in [4].

2.5.1. Reduction of False Loss Alerts

There are three types of "false" loss alerts:

1. Wind shear with loss alerts (WSA) when there is no wind shear with loss.
2. Microburst alerts (MBA) when there is no wind shear with loss.
3. Microburst alerts when there is a wind shear with loss, but the true loss value is below 30 knots, so the alert should have been issued as a WSA.

The first two types are clearly false alerts. The third type of false alert is not, strictly speaking, a false alert; it is an over warning. The reduction of strictly false loss alerts is discussed in this section. The reduction of over warning is accomplished when each system is issuing a loss alert for an operational runway and the integration algorithm joins the two loss estimates. This is discussed in the section entitled Joining Loss Alerts.

Less than 10 percent of the WSA with loss alerts from either TDWR or LLWAS are false, and both systems have fairly high detection rates for these weak loss events. This allows the ML algorithm to require confirmation of weak alerts. For a given operational runway, if one system is issuing a WSA with loss below a specified threshold that is within coverage of the other system and the other system is not issuing a loss alert, the alert is canceled. The thresholds are set for each runway. For example, when a runway has poor coverage by TDWR due to a poor viewing angle, the threshold for requiring weak alerts from LLWAS to be confirmed by TDWR is set low. This is done because TDWR will miss some real events on that runway, and we do not want correct LLWAS alerts cancelled based on a TDWR missed detection. Since there is always a chance that a correct alert will be canceled due to a missed detection by the other system, only very weak alerts are subject to this confirmation process.

Weak microburst alerts are subject to a similar confirmation process. However, the consequences of canceling a correct alert at this level are more severe. For this reason, a weak microburst alert that is not confirmed by a loss alert from the other system is downgraded to a 25–knot wind shear with loss alert instead of being cancelled. Again, the thresholds are set for each runway.

2.5.2. Alert Arbitration Between Loss and Gain Alerts

Alert arbitration is used to decide which alert to issue in the case that one system is issuing a loss alert and the other is issuing a gain alert for the same operational runway. Two guiding principles are used. First, loss events are the more serious safety hazard unless the gain event is sufficiently stronger than the loss event. If the loss event is at the microburst level, the loss event is always judged to be the more serious safety hazard. Second, changes between loss alert and gain alert should be minimized. This is done by modifying the arbitration logic so that at each alert time it is easier to issue an alert of the same type as the last alert than it is to issue an alert of the opposing type.

More precisely, suppose we have both a loss alert and a gain alert for an operational runway. If the loss alert is a microburst alert the arbitration issues the loss alert. If the loss alert is at the wind shear level, there are three cases.

Case 1: Suppose there were no alert for the last alert time. Then the loss alert is issued unless the gain alert is stronger than the loss alert by 15 knots or greater.

Case 2: Suppose there were a loss alert for the last alert time. Then the loss alert is issued unless the gain alert is stronger than the loss alert by 20 knots or greater. That is, if the last alert were a loss alert the arbitration makes it harder for a gain to override the loss than in case 1. This reduces the likelihood of switching alert types from loss to gain.

Case 3: Suppose there were a gain alert for the last polling cycle. Then the loss alert is issued unless the gain alert is stronger than the loss alert by 10 knots or greater. In this case the arbitration makes it easier to continue issuing a gain alert, or rather, it makes it harder for the system to switch alert types from gain to loss.

The thresholds in the three cases above are determined by a basic threshold; in this case, 15 knots. This threshold is adjusted up or down by a set amount; in this case 5 knots, depending on the alert that was issued for the last polling cycle. These values are set during system initialization. They are user selectable, and these are the current recommended values.

2.5.3. Joining Loss Alerts

When both systems are issuing loss alerts for the same operational runway, the integrated loss estimate is an average of the two values. However, care must be taken to avoid issuing a serious underestimate of the strength of the event should one system issue a seriously low estimate. While it is important that the issued loss value accurately reflect the true strength of an event, it is considered a greater safety hazard to underestimate an event than it is to overestimate an event. Provided the alert locations are within LLWAS coverage, the integrated loss value is set to:

$$\text{minimum}\{\text{ average loss value, } K_1 \times \text{LLWAS loss value, } K_2 \times \text{TDWR loss value}\}.$$

For this study, the values of K_1, and K_2 are set to 0.8. The minimum is used since these are negative values. This means that the average value is issued unless the average is less than 80 percent of the largest value from either system. The integrated loss estimate cannot be adjusted downward more than 20 percent from the strongest of the two alerts. If the TDWR alert location is outside LLWAS coverage, the integrated loss estimate is the maximum of the two alerts. When a substantial portion of the outflow is outside the LLWAS network, it is not deemed safe to average the two loss estimates.

2.5.4. Joining Gain Alerts

The mathematics used to compute the integrated gain estimate when both systems are issuing a gain alert for the same operational runway is similar to the mathematics used to integrate loss estimates. However, the the parameters are set to achieve an estimate using a very different logic. Provided both alerts are within LLWAS coverage, the integrated gain estimate is set to:

$$\text{maximum}\{\text{average gain value},\ K_1 \times \text{LLWAS gain value},\ K_2 \times \text{TDWR gain value}\}.$$

Here, K_1 is set to one and K_2 is set to zero. This causes the LLWAS gain alert to always be chosen if the event is inside LLWAS coverage. If the TDWR gain location is outside LLWAS coverage, the integrated gain estimate is the maximum of the two estimates. The mathematics allows the algorithm to incorporate the TDWR gain estimate in the future if TDWR is upgraded to provide more reliable gain estimates.

2.6 Union

The Union algorithm is a message level algorithm that issues the strongest alert from either system for each operational runway. Any loss alert overrides any gain alert, and no attempt is made to reduce false alerts or to adjust the loss or gain estimates. This simple algorithm is used as a baseline for measuring the benefits of the other integration algorithms as they increase in complexity and cost from ML to PL–B to PL–A.

3. TESTBED

The data for this study were collected at the Lincoln Laboratory testbed at the Orlando International Airport (MCO). The testbed layout is shown in Figure 1.

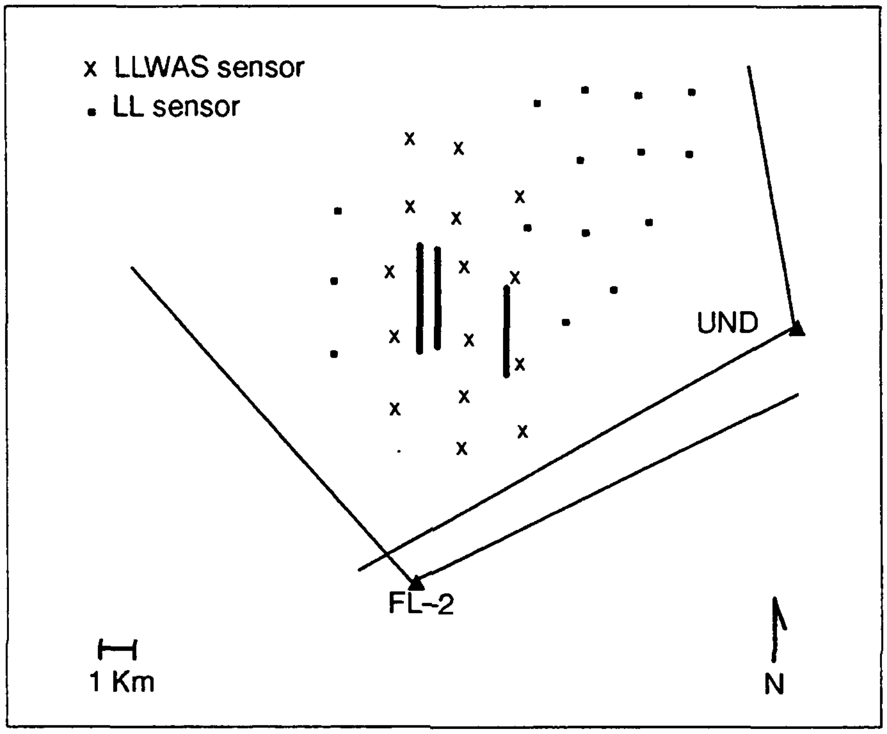

Figure 1. 1991 Orlando testbed.

3.1. LLWAS Data

The LLWAS data were collected from three anemometer networks: six–sensor LLWAS, nine–sensor LLWAS, and 15–sensor LL mesonet. The six–sensor LLWAS network is the Phase II LLWAS used by the FAA to provide wind shear detection coverage for MCO. The six commissioned sensors were moved to sites chosen for the LLWAS 3 and placed on LLWAS 3 poles. The nine–sensor anemometer network is a non–commissioned Phase II LLWAS that has been modified to poll nine sensors. It consists of nine sensors that are to be added to the original six sensors to complete the LLWAS 3 for MCO. A 15–sensor anemometer network on 100–foot poles was installed by MIT Lincoln Laboratory to enlarge the coverage region.

The asynchronous data from the three networks were merged into ten–second synchronous archive records. Each record contains the sensor winds at all 30 sensors for a 10–second time period. The resulting data records are similar to the data records in the LORAL Data Systems LLWAS III. Each record contains the most recent data from each sensor during the previous ten seconds. Missing and/or corrupted data were flagged in the archive.

3.2. TDWR Data

The Lincoln Laboratory TDWR testbed radar (FL–2C) provided the TDWR base data. The TDWR products needed for the product level integration algorithms were collected during normal FL–2C operations. TDWR alerts were generated using the TDWR runway alert algorithm both with and without flight path shear integration.

The TDWR microburst shapes and alert values needed by PL–A were generated by software provided by NCAR.

3.3. Dual–Doppler Data

The radar data used to generate the dual–Doppler wind fields were collected from FL–2C and the University of North Dakota Doppler radar (UND). The FL–2C radar scanned the standard TDWR coverage region mandated for MCO. The UND scan sector was chosen to completely cover the anemometer network. Dual–Doppler data were available in 1991 only. In 1992, the UND Doppler data were not of sufficient quality to produce dual–Doppler wind fields.

3.4. Weather Summary

It is important to have enough cases so that the evaluation is statistically significant. The 20 days used in this study were chosen because they contained an assortment of wind shear events, from strong microbursts to marginal wind shears. They also had complete data, allowing a good set of comparison alerts to be generated. Tables 1 and 2 give summary accounts of the wind shear events for the twenty days. The approximate numbers of runway minutes of alerts is the number of polls of alerts divided by six, the number of polls per minute. If a 10–minute event impacts three runways, there are 30 runway minutes of impact. The maximum loss is the maximum loss experienced on any runways during the day as determined from the comparison alerts (See Section 4.).

Table 1.
1991 Weather Summary
(Date, Approximate Runway Minutes of Alerts, Maximum Loss)

Date	MBA	WS/ LOSS	WS/ GAIN	Max Loss (knots)
7/10/91	27	94	18	–66
7/17/91	70	58	42	–44
7/25/91	0	45	213	–29
7/30/91	0	74	0	–36
8/2/91	35	357	57	–40
8/3/91	3	219	5	–45
8/9/91	245	184	58	–89
8/10/91	64	179	29	–62
8/31/91	258	161	83	–52
9/7/91	4	349	126	–32
Total	706	1720	631	

Table 2.
1992 Weather Summary
(Date, Approximate Runway Minutes of Alerts, Maximum Loss)

Date	MBA	WS/ LOSS	WS/ GAIN	Max Loss (knots)
6/2/92	0	244	0	−38
6/3/92	97	539	99	−40
6/12/92	0	39	3	−29
6/21/92	81	359	313	−51
6/30/92	108	496	264	−47
7/7/92	249	484	178	−63
7/19/92	36	651	132	−56
8/1/92	281	803	585	−65
8/3/92	129	562	317	−49
8/14/92	179	359	89	−79
Total	1160	4536	1980	

4. EVALUATION METHODOLOGY

The alert type and loss/gain estimate from each algorithm alert was compared against a comparison alert generated from Doppler measurements along the flight path of the given operational runway. The results of this comparison were used to generate performance measures such as probability of detection, probability of false alert, and overall system accuracy. In 1991, the comparison alerts were generated from a dual–Doppler–based wind shear detection algorithm. This allowed an evaluation for runways that are not aligned with the TDWR line of sight. In 1992, comparison alerts were generated in a manner similar to 1991, but due to UND data quality problems, only TDWR data were used. This limited the 1992 evaluation to runways aligned with the TDWR line of site. Comparison alerts from either the dual–Doppler algorithm or direct Doppler measurements along the flight path, while not perfect, provide a good estimate of the actual wind shear conditions.

The three real runways at MCO cover only a small region limiting the number of microburst impacts. Furthermore, TDWR is is sited to look directly down the real runways, which is an especially advantageous situation for the TDWR algorithm. In 1991, 14 imaginary runways were laid out in the region covered by the anemometer network to capture additional microburst impacts and to give an assortment of runways at different angles to the TDWR line of sight. In 1992, two imaginary runways oriented north/south were used in addition to the real runways.

4.1. Dual Doppler

Dual–Doppler alerts are constructed in three steps:

1. Compute a two–dimensional wind field by combining observations from two radars.
2. Compute runway alerts from each dual–Doppler wind field.
3. Interpolate the runway alerts in time to produce dual–Doppler alerts at the time of the algorithm alerts.

The two–dimensional wind field is computed using standard dual–Doppler analysis [1]. To do this processing, the observations from the radars must be nearly simultaneous, and the directions from the point of interest to the two radars must be substantially different. Dual–Doppler computations are done for each point in a grid covering the area of interest. The grid spacing used was 150 meters.

Once the two–dimensional wind field has been computed, loss alerts and gain alerts are computed for each operational runway flight path. This is done by computing the runway oriented components of each wind vector near a flight path and using these components to find the maximum sustained loss and the maximum sustained gain with shears above specified thresholds.

Two sets of dual–Doppler alerts are computed. One set is computed using dual–Doppler data points within a narrow (300 meter wide) corridor. The other set is computed using dual–Doppler data

points within a wide (1800 meter wide) corridor. Each corridor covers a runway and extends out from the runway 3 nm for arrival runways and 2 nm for departure runways. The loss alerts generated for the narrow corridor require a shear above 2.5 m/s/km and the gain alerts require a shear above 1.9 m/s/km. These shear thresholds correspond to a loss of 20 knots over a distance of 4 km and a gain of 15 knots over 4 km, which are the standard minimum hazardous shear thresholds. The loss alerts generated for the wide corridor require a shear above 2 m/s/km and the gain alerts require a shear above 1 m/s/km.

The viewpoint of the study is that a dual–Doppler alert in the narrow corridor must be matched by an algorithm alert and that an algorithm alert is not considered false if it is matched by a dual–Doppler alert in the wide corridor. That is, if the dual–Doppler algorithm detects a loss with a strong shear on the flight path, an algorithm must issue an alert or it will be counted as missing a detection. Such an event is clearly a hazard and must be detected. Conversely, if the dual–Doppler algorithm detects a loss with a low shear or one that is well to the side of the center line, the event is marginal and an algorithm need not issue an alert. If an alert is issued for a marginal event, it is not counted as false since some loss with shear is present.

Since a dual–Doppler analysis is available approximately every 60 seconds and algorithm alerts are issued every 10 seconds, linear interpolation between dual–Doppler alert values is used to find the dual–Doppler alert value at the time of the algorithm alert. We required the time difference between the dual–Doppler analyses just before and after the algorithm alert time be less than 90 seconds. If the difference is greater, wind shear values can fluctuate enough to make linear interpolation questionable.

4.2. Alert Statistics

Alert statistics such as probability of detection (POD) and probability that an issued alert is false (PFA) are computed by comparing algorithm alerts to a set of comparison alerts. Each operational runway is in one of four alert states, microburst (MBA), wind shear with loss (WSL), wind shear with gain (WSG), and no alert (Null). The alert statistics assess the ability of an algorithm to place a runway in the same alert state as the comparison alert.

Computing alert statistics for each algorithm consists of three steps:

1. Build contingency tables.
2. Compute detection statistics from contingency tables.
3. Compute false alert statistics from contingency tables.

4.2.1. Contingency Tables

Figure 2 shows an example of a contingency table. Each row of a contingency table represents a different alert state as determined by the algorithm: MBA, WSL, WSG, or Null. The columns represent the same alert states for the comparison alerts. The table entries are filled by comparing each

		comparison alert state			
		MBA	WSL	WSG	Null
algorithm alert state	MBA				
	WSL				
	WSG				
	Null				

Figure 2. Contingency table.

algorithm alert to its associated comparison alert and incrementing the appropriate entry. After matching all of the alerts the table contains a count for each alert pair. These counts are then used to compute the various system performance probabilities.

During the Doppler processing, the data are smoothed and interpolated to the grid points of interest. This causes errors in the resulting wind field. Additional errors in the comparison alerts are introduced by the temporal interpolation. A margin of error of ± 5 knots was used in building the contingency table to account for these inaccuracies.

Figure 3 illustrates the effects of this margin of error. For poll 1 only a Null alert is considered correct. For polls 2 and 3 only a Null alert or a WSL alert is considered correct. For poll 4 only a WSL alert is considered correct. For polls 5 and 6 only a WSL alert or an MBA alert is considered correct. And for poll 7 only an MBA alert is considered correct. For example, given a 30–knot algorithm alert and the 27–knot comparison alert, both alerts are tallied as microburst alerts. Thus, the counter corresponding to the first row and first column would be incremented by one.

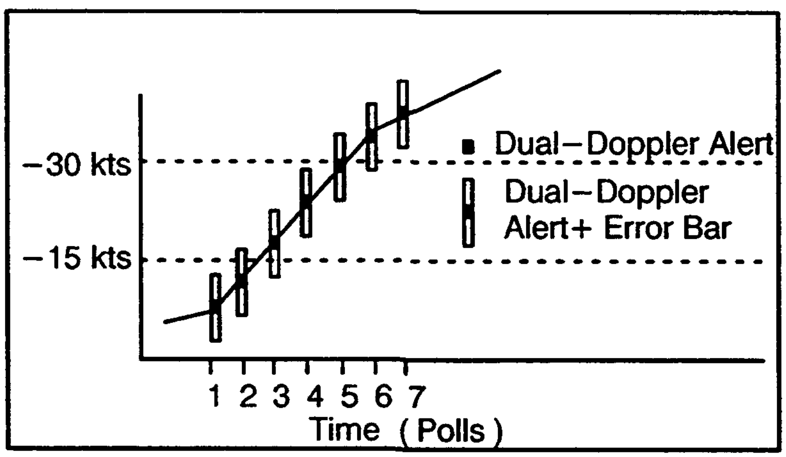

Figure 3. Effect of the 5–knot uncertainty in dual–Doppler alerts.

4.2.2. Computation of Detection Statistics

Three measures of detection were used to evaluate each algorithm: the probability of a loss given a microburst–POD(L|MB), the probability of a loss given a microburst or a wind shear with loss–POD(L|L), and the probability of a microburst given a microburst–POD(MB|MB). These are computed from the contingency table built using comparison alerts from the narrow runway corridor.

The POD(L|MB) is the probability that either a WSL or an MBA was issued when the comparison alert indicates an MBA. This is computed from the contingency table by taking the sum of the first two rows of the first column and dividing by the total of all the elements in the first column.

The POD(L|L) is the probability that either a WSL or an MBA was issued when the comparison alert indicates a WSL or an MBA. This is computed from the contingency table by summing the four elements in the first two rows of columns one and two and dividing by the total of all the elements in the first two columns.

The final detection statistic, POD(MB|MB), is the probability that an MBA was issued when the comparison alert indicates an MBA. This is computed from the contingency table by taking the element in the first row, first column and dividing by the total of all the elements in the first column.

4.2.3. Computation of False Alert Statistics

Four false alert statistics were used to evaluate each algorithm: the probability of false microburst (PFA(MB)), the probability of false wind shear (PFA(WSL)), the probability of false loss–PFA(L), and the probability of microburst over warning (OW(MB)). These are computed from the contingency table built using comparison alerts from the wide runway corridor.

The PFA(MB) is the probability that an MBA was issued when the comparison alert indicates no loss. This is computed from the contingency table by taking the sum of the last two columns of the first row and dividing by the total of all the elements in the first row.

The PFA(WSL) is the probability that a WSL alert was issued when the comparison alert indicates no loss. This is computed from the contingency table by taking the sum of the last two columns of the second row and dividing by the total of all the elements in the second row.

The PFA(L) is the probability that a WSL or an MBA alert was issued when the comparison alert indicates no loss. This is computed from the contingency table by summing the four elements in the last two columns of rows one and two and dividing by the total of all the elements in the first two rows.

The final statistic, OW(MB), is the probability that an MBA alert was issued when the comparison alert indicates a WSL. That is, the alert, while not false, is an incorrect use of MBA. This is computed from the contingency table by taking the second element in the first row and dividing by the total of all the elements in the first row.

4.3. Loss Accuracy Histograms

Another important measure of system performance is the ability of an algorithm to correctly estimate the loss associated with a wind shear. This is evaluated by constructing a histogram of differences between algorithm loss estimates and comparison alert loss estimates. First the difference between each comparison alert value and corresponding algorithm alert value is computed. Then the histogram is built by dividing the range of differences into five–knot bins and keeping count of the number of differences that fall into each bin.

There are three principal characteristics of the accuracy histograms. The first is the bias, or how closely the peak of the histogram coincides with the center bin of differences. The second is skewness, or how symmetric the distribution is. Any bias or skewness in the histogram indicates a tendency to under warn or over warn. The third is variance, or how much the accuracy values are spread out among the bins. Ideally, the bin values should cluster strongly around the central bin.

During the process of building the histograms we also compute the fraction of loss estimates that are within 5 knots, 10 knots, etc., of the comparison alert loss estimates.

5. RESULTS

5.1. Alert Statistics

In 1991, TDWR, LLWAS 3, and four integration algorithms were evaluated on 10 days. Alerts were generated for a variety of runways, both parallel and non–parallel to the TDWR line of sight. TDWR, and thus the integration algorithms, are expected to perform best on runways parallel to the TDWR line of sight, so the other runways are included to test the algorithms in a more difficult environment. Results are reported for the parallel runways, non–parallel runways, and all the runways as a group.

The real runways at MCO are all parallel to the TDWR line of sight and are in the coverage region of the LLWAS sensors. The non–parallel runways have LLWAS coverage provided by the Lincoln anemometer network. The data quality from this network is not as high as the data quality from a commissioned LLWAS 3 network. The data are of sufficient quality for algorithm comparison since any degradation in performance will be experienced by each integration algorithm. The LLWAS 3 performance numbers for the non–parallel runways should be considered conservative estimates of the true performance of the system.

The data set for runways that are parallel to the TDWR line of sight is much more extensive than the data set for the non–parallel runways due to problems with the Lincoln anemometer network. Only 6 percent of the MBA and 22 percent of the WS/Loss occur on non–parallel runways. This gives greater statistical significance to the performance results for the parallel runways. The results for the non–parallel runways, while not as statistically significant, especially for measures related to MBA, provide insight to the relative benefits of the different integration algorithms.

5.1.1. 1991 Without Flight Path Shear Integration

The TDWR deployed with LLWAS 3 systems will use flight path shear integration. The alert statistics, shown in Tables 3 through 5, obtained without flight path shear integration are included in this study because the PL–A algorithm software did not use flight path shear integration.

The detection statistics are very high for each algorithm. The probability of issuing a loss alert when a microburst strength wind shear is present on the flight path is above 90 percent, the required minimum detection level. A more demanding metric is the probability of issuing an MBA when a microburst strength wind shear is present on the flight path. Each algorithm achieves 90 percent or above for this metric as well.

The maximum allowed PFA(L) is 10 percent. TDWR without flight path shear integration does not meet this minimum, having a PFA(L) of 15 percent overall, and 38 percent on those runways that are not parallel to the TDWR line of sight. Despite varying success at removing false alerts, some of these false alerts carry through the integration algorithms, each of which fails to achieve the 10 percent maximum.

Both the PL–B and ML algorithms issue fewer false microburst alerts, the most serious of the false alerts, than the Union algorithm. Of the four integration algorithms, ML has the lowest PFA(MB) at two percent, and PL–A has the highest PFA(MB) at six percent.

ML, with a PFA(WS) of 19 percent, is the only integration algorithm with a lower PFA(WS) than the Union algorithm. Of the four integration algorithms, PL–A has the highest PFA(WS) at 23 percent.

TDWR without flight path shear integration has a bias towards issuing loss alert values that are greater than the alert values determined from the dual–Doppler algorithm. This can be seen from the loss accuracy histograms that follow. This gives rise to a microburst over warning (OW(MB)) of 31 percent for TDWR. LLWAS also tends to over warn. This is due primarily to the compensation for the sparseness of the anemometer network, not a high bias. The microburst over warning of both TDWR and LLWAS causes the integration algorithms to over warn as well. Both PL–B and ML issue fewer microburst over warnings than the Union algorithm. Of the four integration algorithms, ML has the lowest OW(MB) at 27 percent, and PL–A has the highest OW(MB) at 37 percent.

Table 3.
1991 Probability Statistics
Without Fight Path Shear Integration
Runways Parallel to TDWR Line of Sight

	TDWR	LLWAS	UN	PL–A	PL–B	ML
POD(L|MB)	99	97	99	98	100	99
POD(L|L)	93	77	94	93	94	93
POD(MB|MB)	97	91	98	97	99	97
PFA(MB)	3	2	4	4	2	1
PFA(WS)	11	1	11	13	12	10
PFA(L)	7	2	7	8	7	6
OW(MB)	28	22	30	32	29	24

Table 4.
1991 Probability Statistics
Without Flight Path Shear Integration
Runways Not Parallel to TDWR Line of Sight

	TDWR	LLWAS	UN	PL–A	PL–B	ML
POD(L|MB)	100	92	100	100	100	100
POD(L|L)	87	71	91	93	91	91
POD(MB|MB)	98	85	98	99	99	98
PFA(MB)	17	10	14	16	13	11
PFA(WS)	43	3	43	42	41	36
PFA(L)	38	6	36	33	36	32
OW(MB)	51	51	57	59	53	52

Table 5.
1991 Probability Statistics
Without Flight Path Shear Integration
All Runways

	TDWR	LLWAS	UN	PL–A	PL–B	ML
POD(L|MB)	99	97	99	98	100	99
POD(L|L)	92	76	93	93	94	93
POD(MB|MB)	97	90	98	97	99	97
PFA(MB)	4	3	5	6	4	2
PFA(WS)	22	2	22	23	22	19
PFA(L)	15	2	15	14	15	13
OW(MB)	31	25	33	37	31	27

5.1.2. 1991 With Flight Path Shear Integration

The alert statistics in this section, shown in Tables 6 through 8, more accurately reflect the expected performance of a fielded system since all TDWR co–located with LLWAS 3 will use flight path shear integration. The PL–A algorithm is not evaluated in this section since it did not use TDWR with flight path shear integration.

All of the algorithms detect wind shear with a loss of head wind very well. For each algorithm, the probability of issuing a loss alert when a microburst strength wind shear is present on the flight path is above 90 percent, the required minimum detection level. A more demanding metric is the probability of issuing an MBA when a microburst strength wind shear is present on the flight path. Each algorithm achieves 90 percent or above for this metric as well.

The false alert statistics show a large improvement for TDWR and the integration algorithms when flight path shear integration is used. The maximum allowed PFA(L) is 10 percent. All of the algorithms meet this standard. TDWR still issues an excessive number of false alerts on runways that are not parallel to the TDWR line of sight. The integration algorithms give a slight reduction in the number of false alerts; however, their PFA(L) remains high on these runways.

Both the PL–B and ML algorithms issue fewer false microburst alerts, the most serious of the false alerts, than the Union algorithm. Of the three integration algorithms, ML has the lowest PFA(MB) at one percent, and the Union has the highest PFA(MB) at three percent. ML also has the lowest PFA(WS) at nine percent, and the Union has the highest PFA(WS) at 11 percent.

TDWR with flight path shear integration achieves a much lower OW(MB) than without flight path shear integration. The integration algorithms still must contend with the microburst over warning from LLWAS. Both PL–B and ML reduce microburst over warning relative to the Union algorithm, with ML giving the greatest reduction. Of the three integration algorithms, ML has the lowest OW(MB) at 14 percent, and Union has the highest OW(MB) at 23 percent.

Table 6.
1991 Probability Statistics
With Flight Path Shear Integration
Runways Parallel to TDWR Line of Sight

	TDWR	LLWAS	UN	PL–B	ML
POD(L|MB)	98	97	99	99	98
POD(L|L)	90	77	91	92	90
POD(MB|MB)	96	91	97	98	96
PFA(MB)	0	2	2	1	0
PFA(WS)	1	1	1	1	2
PFA(L)	1	2	2	1	1
OW(MB)	5	22	20	14	12

Table 7.
1991 Probability Statistics
With Flight Path Shear Integration
Runways Not Parallel to TDWR Line of Sight

	TDWR	LLWAS	UN	PL–B	ML
POD(L|MB)	100	92	100	100	100
POD(L|L)	82	71	90	90	88
POD(MB|MB)	91	85	92	91	91
PFA(MB)	13	10	11	13	12
PFA(WS)	31	3	30	28	26
PFA(L)	29	6	26	26	24
OW(MB)	37	51	51	46	41

Table 8.
1991 Probability Statistics
With Flight Path Shear Integration
All Runways

	TDWR	LLWAS	UN	PL–B	ML
POD(L|MB)	98	97	99	100	98
POD(L|L)	89	76	91	92	90
POD(MB|MB)	96	90	97	98	96
PFA(MB)	1	3	3	2	1
PFA(WS)	10	2	11	10	9
PFA(L)	7	2	8	7	7
OW(MB)	8	25	23	17	14

5.1.3. 1992 With Flight Path Shear Integration

In 1992 only TDWR with flight path shear integration, LLWAS 3, and the ML algorithm were tested. Due to poor quality Doppler data from the UND radar, only runways oriented north/south were used in the evaluation. The alert statistics are shown in Table 9.

The detection statistics are slightly below those achieved in 1991. Both TDWR and Message Level achieve a POD(MB) well above 90 percent. LLWAS has a POD(MB) of 87 percent, slightly below the required 90 percent. The LLWAS anemometer network does not extend to the full three miles from the runways, making it very difficult to achieve a 90 percent detection probability over the entire airport region.

The false alert statistics are higher than in 1991. However, the PFA(L) values are well below the maximum allowed value of 10 percent, and each algorithm issues very few false microburst alerts. The microburst over warning statistics are also higher than in 1991.

Table 9.
1992 Probability Statistics
With Flight Path Shear Integration
Runways Parallel to TDWR Line of Sight

	TDWR	LLWAS	ML
POD(L|MB)	96	87	97
POD(L|L)	88	71	86
POD(MB|MB)	86	66	86
PFA(MB)	2	6	4
PFA(WS)	3	3	3
PFA(L)	2	4	4
OW(MB)	17	28	21

5.2. Accuracy Statistics

Results on the accuracy of the loss estimates are reported in two forms. Both relate to the accuracy of the loss estimates for times and runways where the comparison alerts indicate a microburst level hazard. The first form is a table giving the percentage of algorithm alerts with a loss estimate within a fixed number of knots of the comparison alert loss estimate, and the median error in knots. This gives an overall assessment of system accuracy and bias. The second form are histograms giving the percentage of alerts that differ from the comparison alert values by a multiple of 5 knots ± 2.5 knots.

5.2.1. 1991 Without Flight Path Shear Integration

Table 10 gives the percentage of alerts that fall within a range of the loss estimate from its associated comparison alert and the median error in knots. The table shows LLWAS is more accurate

than TDWR without flight path shear integration. The integration algorithms are slightly more accurate than TDWR, but none are as accurate as LLWAS. The ML algorithm is significantly more accurate than the other integration algorithms.

**Table 10.
1991 Accuracy Statistics
Without Flight Path Shear Integration**

	TDWR	LLWAS	Union	PL–A	PL–B	ML
% ± 2.5 knots	8	16	8	8	8	17
% ± 7.5 knots	28	50	28	31	28	43
% ± 12.5 knots	53	74	54	59	54	63
% ± 17.5 knots	70	88	71	76	71	78
median error (kts)	11.7	3.5	11.6	10.7	11.6	8.6

Figure 4 shows that TDWR without flight path shear integration consistently over estimates the strength of the loss associated with microburst level events, being centered at 11.7 knots. This is the expected result; complaints of microburst overwarning led to the development of the flight path shear integration algorithm to refine the TDWR loss estimates.

Figure 5 shows that LLWAS on average produces accurate loss estimates, with a histogram centered at 3.5 knots. The wide spread of values is the result of the undersampling of the microburst outflow due to the sparseness of the anemometer network, and the corresponding statistical correction for the undersampling. The LLWAS results are independent of flight path shear integration.

Figures 6 and 7 for the Union and PL–B integration algorithms are very similar to the histogram for TDWR. The fact that these algorithms do not produce a significant increase in the over estimation

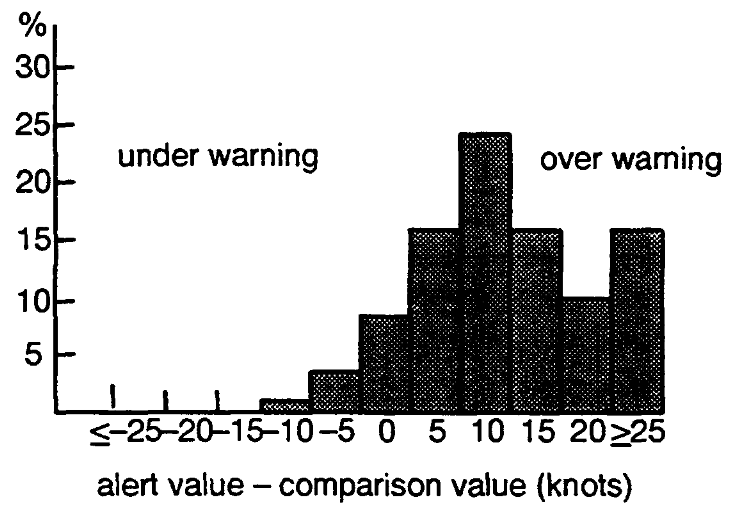

Figure 4. 1991 TDWR loss accuracy histogram without flight path shear integration.

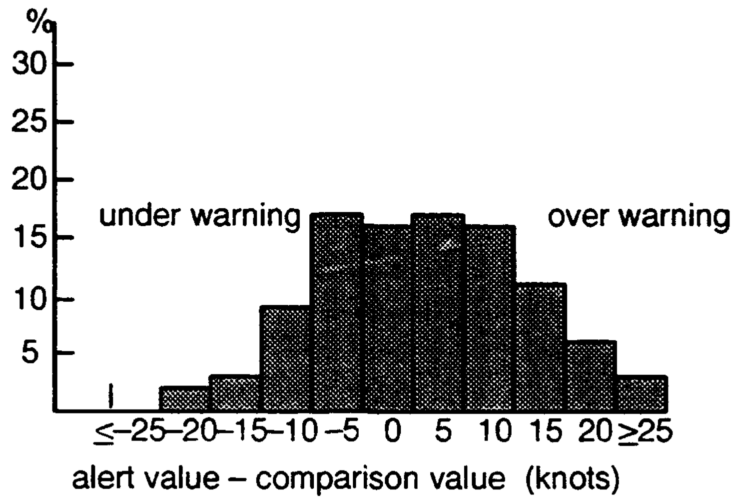

Figure 5. 1991 LLWAS loss accuracy histogram.

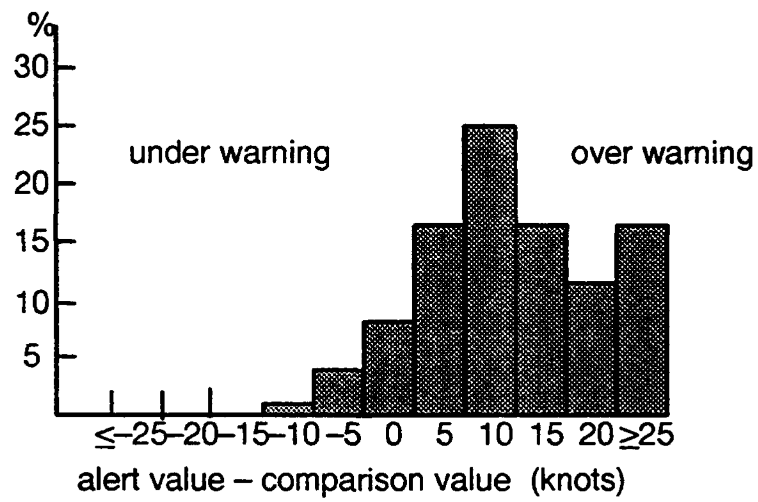

Figure 6. 1991 Union (PL–B) loss occuracy histogram without flight path shear integration.

of the loss values relative to TDWR arises because the TDWR alerts are nearly always stronger than the LLWAS alerts so the integrated alert values are usually the TDWR alert values. Figure 8 shows that the averaging of matched loss estimates by the ML algorithm has reduced the amount of the over estimation of the loss value, however a significant amount remains.

5.2.2. 1991 With Flight Path Shear Integration

The TDWR flight path shear integration algorithm was developed to reduce the over estimation in the TDWR loss estimates. Figure 9 and table 11 show that with this algorithm TDWR produces more accurate loss estimates without incurring a significant amount of underwarning. TDWR issues loss estimates that are closer to the comparison loss estimates than LLWAS, although TDWR has

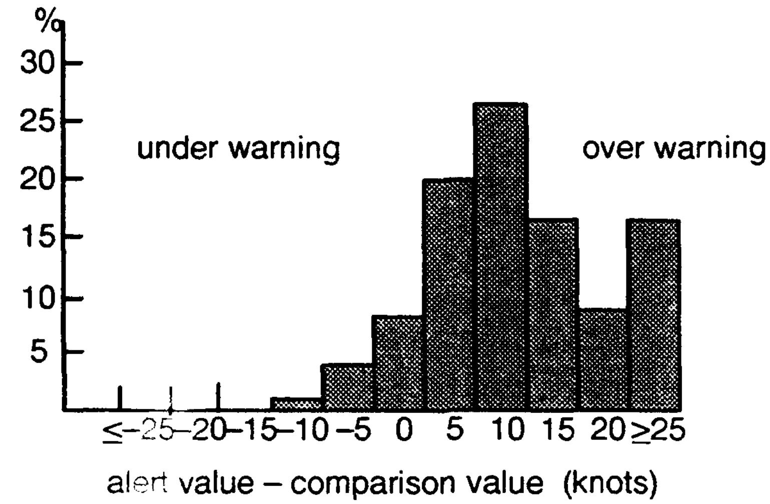

Figure 7. 1991 PL–A loss accuracy histogram without flight path shear integration.

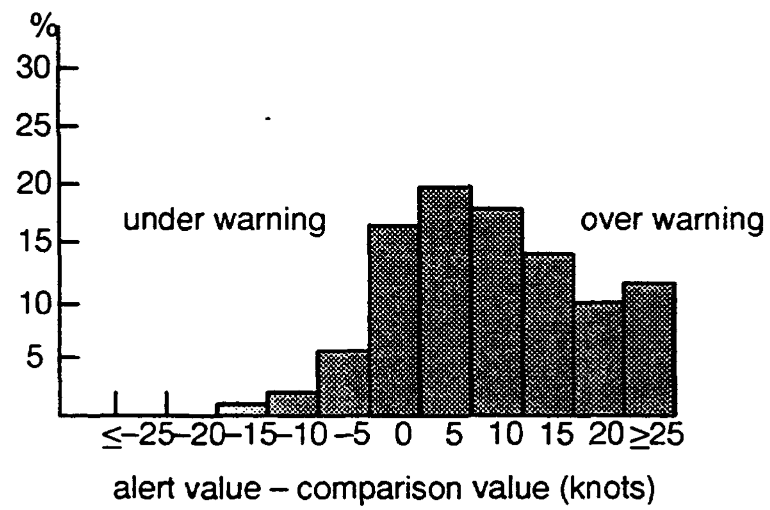

Figure 8. 1991 ML loss accuracy histogram without flight path shear integration.

a larger median error than LLWAS. This apparent discrepancy arises from the larger spread of the errors in the LLWAS loss estimates relative to the spread of errors in the TDWR loss estimates, as seen in figures 5 and 9. The percentage of loss estimates from the Union and PL–B algorithms near the loss estimates from the comparison alerts are similar to those for LLWAS, although their median errors are larger. The ML algorithm has the highest accuracy of the integration algorithms and produces more accurate loss estimates than TDWR and LLWAS by most measures.

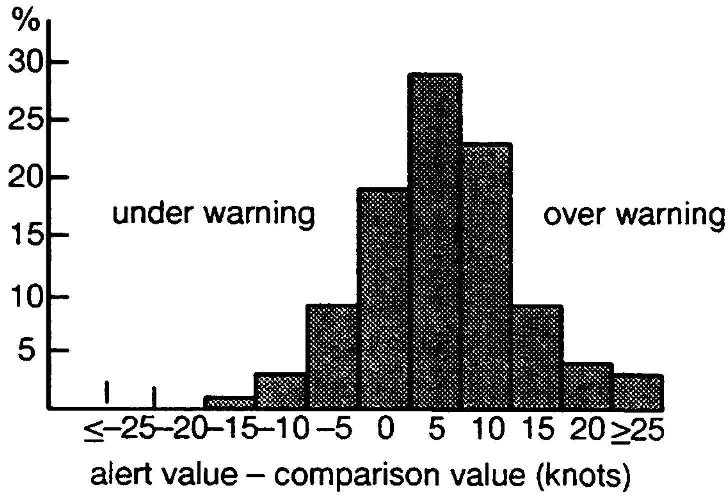

Figure 9. 1991 TDWR loss accuracy histogram with flight path shear integration.

Table 11.
1991 Accuracy Statistics
With Flight Path Shear Integration

	TDWR	LLWAS	Union	PL–B	ML
% ± 2.5 knots	19	16	15	16	23
% ± 7.5 knots	57	50	47	49	60
% ± 12.5 knots	83	74	75	76	81
% ± 17.5 knots	93	88	89	90	93
median error (kts)	5.6	3.5	7.5	7.1	4.6

Figure 9 shows that TDWR with flight path shear integration has a high bias, but this bias is less than before flight path shear integration was added. The histogram is nearly symmetric, and centered at 5.6 knots. The results in figure 5 still hold for LLWAS, since LLWAS is not affected by the introduction of flight path shear integration. Figures 10 and 11 show that both the Union and PL–B algorithms have a higher bias than either TDWR or LLWAS. Their histograms are nearly symmetric, centered at 7.5 knots and 7.1 knots, respectively, and have a spread similar to the histogram for TDWR. Figure 12 shows that the ML algorithm has a high bias, although it is reduced from both TDWR and the other integration algorithms and approaches the bias in LLWAS. The ML histogram is nearly symmetric and has a spread similar to the histogram for TDWR.

5.2.3. 1992 With Flight Path Shear Integration

The accuracy statistics for 1992 indicate that the performance of the systems was not as good as in 1991. Table 12 gives the accuracy statistics for TDWR with flight path shear integration,

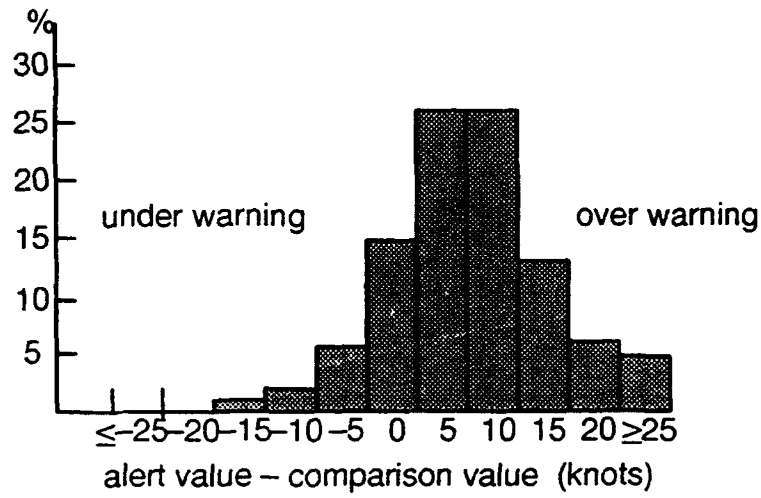

Figure 10. 1991 Union TDWR loss accuracy histogram with flight path shear integration.

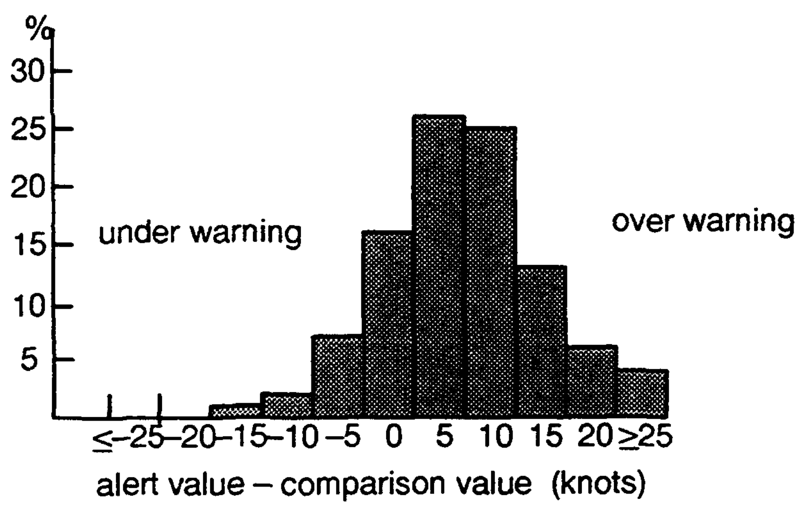

Figure 11. 1991 PL–B loss accuracy histogram with flight path shear integration.

LLWAS 3, and the ML algorithm. Unlike in 1991, LLWAS produced more accurate loss estimates than TDWR as measured by both distribution of errors and median error. The performance of the ML algorithm is between that of LLWAS and TDWR.

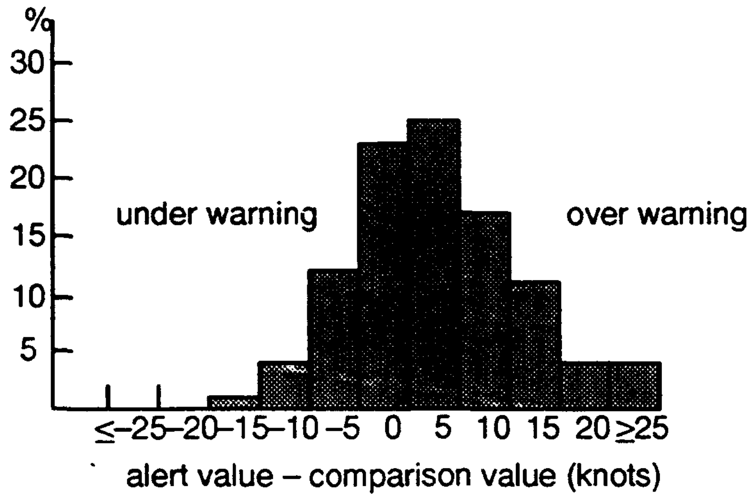

Figure 12. 1991 ML loss accuracy histogram with flight path shear integration.

Table 12.
1991 Accuracy Statistics
With Flight Path Shear Integration

	TDWR	LLWAS	ML
% ± 2.5 knots	15	18	15
% ± 7.5 knots	43	47	45
% ± 12.5 knots	68	70	70
% ± 17.5 knots	84	87	86
median error (kts)	7.6	5.3	7.2

Figure 13 shows a higher bias in TDWR than in 1991. The histogram is centered at 7.6 knots and is fairly symmetric. Figure 14 shows that LLWAS in 1992 also had a higher bias than in 1991, although the spread of values is reduced. The LLWAS histogram is centered at 5.3 knots, giving a lower bias than TDWR. Figure 15 shows that the ML algorithm has a smaller spread than either TDWR or LLWAS and is centered at 7.2 knots.

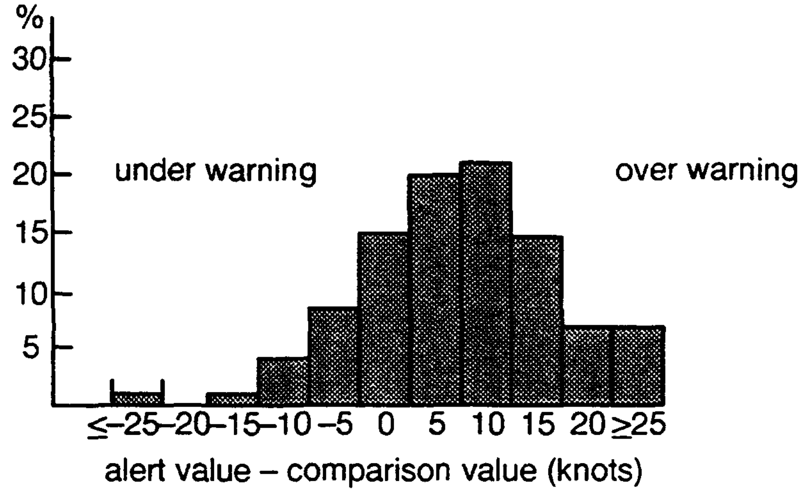

Figure 13. 1992 TDWR loss accuracy histogram with flight path shear integration.

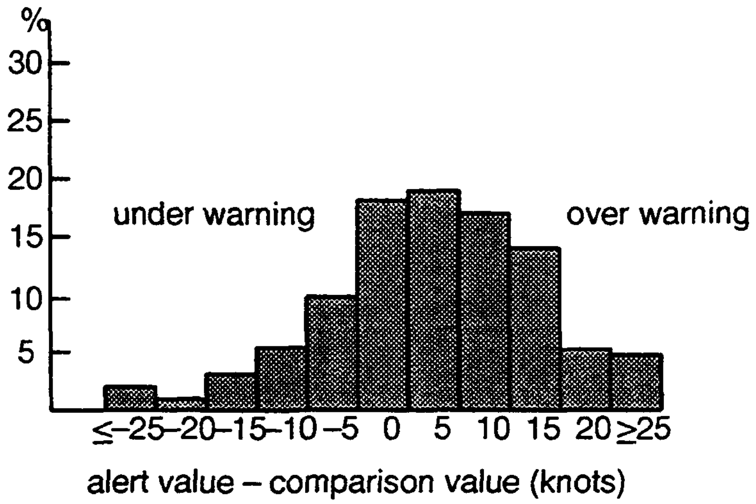

Figure 14. 1991 LLWAS loss accuracy histogram.

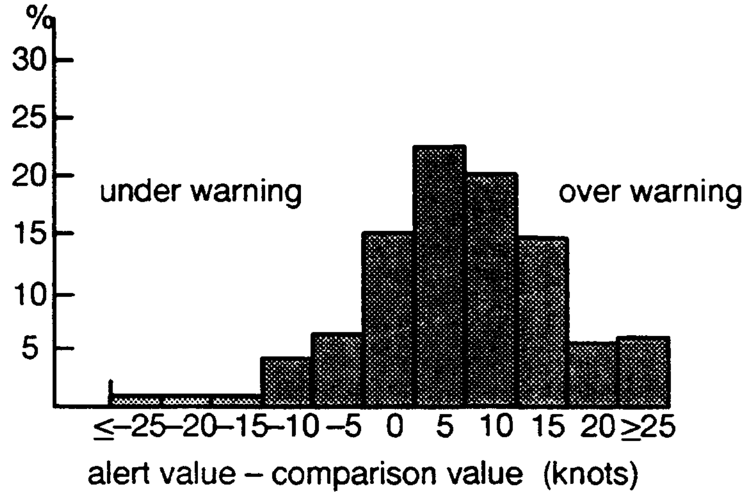

Figure 15. 1992 ML loss accuracy histogram with flight path shear integration.

6. CONCLUDING REMARKS

Each of the algorithms performed very well. With the introduction of the flight path shear integration to TDWR, all of the integration algorithms easily bettered the required 90 percent probability of detection for microburst level wind shear events, with less than the 10 percent maximum allowed false alert percentage when considered over all runways studied. All of the algorithms have a high bias, but at levels that are not detrimental to airport operations. By each measure studied, the ML integration algorithm provided performance superior to the other integration algorithms.

Based on an extensive review of the algorithms, evaluation methodology, and results, NCAR and Lincoln Laboratory issued a joint recommendation to the FAA that the ML algorithm be chosen as the production TDWR/LLWAS 3 integration algorithm. Raytheon is incorporating this algorithm into build 5 of the TDWR software.

The excellent performance reported for TDWR and LLWAS 3 is due in part to the test location. The Orlando environment is particularly favorable to wind shear detection algorithms. Microbursts there are usually large, symmetric, and have a high moisture content and so are easier for the integration subsystems to detect. However, even in a benign environment, integration has an advantage over LLWAS 3 in detection of wind shear with a loss of head wind due to TDWR's greater coverage region and spatial density of data. Integration also has an advantage over TDWR due to LLWAS 3's rapid update rate and superior ability to detect wind shear with a gain of head wind, which was not considered in this study.

In 1992, NCAR conducted an operational demonstration of the ML algorithm at Stapleton International Airport. The NCAR results in Denver show the benefits of integrating TDWR and LLWAS 3 are much greater in that environment than in Orlando [7].

ACRONYMS AND ABBREVIATIONS

ARTCC	Air Route Traffic Control Center
FAA	Federal Aviation Administration
GMT	Greenwich Mean Time
kt	knot
LLWAS 3	Low Level Wind Shear Alert System, third generation
MB	Microburst
MBA	Microburst Alert
MCO	Orlando International Airport
MIT/LL	MIT Lincoln Laboratory
ML	Message Level algorithm
NCAR/RAP	National Center for Atmospheric Research/Research Applications group
Null	No alert
OW	Over Warning
PFA	Probability of False Alert
PFA(L)	Probability of False Alert (Loss)
PFA(MB)	Probability of False Alert (Microburst)
PFA(WS)	Probability of False Alert (wind shear)
PIREP	Pilot Report
PL–A	Product Level–A algorithm
PL–B	Product Level–B algorithm
POD	Probability of Detection
TDWR	Terminal Doppler Weather Radar
TRACON	Terminal Radar Approach Control
UND	University of North Dakota
WSA	Wind Shear Alert
WSL	Wind Shear with Loss
WSG	Wind Shear with Gain

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APPENDIX A

A PIREP-BASED ANALYSIS OF AN INTEGRATED TDWR/LLWAS ALERT SYSTEM EVALUATED AT ORLANDO INTERNATIONAL AIRPORT DURING THE SUMMER OF 1992

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During the summer of 1992, the Terminal Doppler Weather Radar (TDWR) Program evaluated a system that provided wind shear and microburst alerts to pilots landing and departing from Orlando International Airport. The demonstration took place over the 65-day period starting May 4 and ending July 7. For a majority of the alert periods, tapes of the pilot/Local Control radio communication channels were obtained for analysis. The tapes provided a portrayal of airport runway operations during the alert periods, including any pilot reports (PIREPs) of weather-related encounters.

This appendix presents the results of an operational analysis of the radio communication tapes and other materials, and represents one component of the overall evaluation. The study pursued two lines of investigation: (1) what happened operationally during the alert periods, and (2) what would have been the operational impact of alternative alert schemes?

Relative to "what happened operationally," the primary findings are:

- The tested ***system performed well*** overall, based on pilot reports, and
- There were ***two surprises resulting in recommendations*** concerning the issuance of alerts by controllers.

Relative to "the operational impact of alternative alert schemes," the primary findings are:

- The ***post-1990 software changes significantly improved*** the quality of the alert service provided by TDWR, and
- ***System integration provides a superior overall alert service*** over what would be provided by either TDWR or the Phase-3 Low Level Wind Shear Alert System (LLWAS) as stand-alone alert systems.

The U.S. Department of Transportation, Federal Aviation Administration, ANR-150, sponsored the work presented in this appendix. The Volpe National Transportation Systems Center of the U.S. Department of Transportation conducted the operational analysis. The Massachusetts Institute of Technology's Lincoln Laboratory provided technical support.

BACKGROUND

Wind shear in general and microbursts in particular are of concern to landing and departing pilots. One FAA activity addressing this concern is the development of TDWR.

The 1992 demonstration was one of a series of such demonstrations conducted by the TDWR Program since 1988. The series has served as a vehicle for perfecting the basic TDWR system and associated weather products and for investigating advanced TDWR-related system

concepts and services. The 1992 demonstration involved an Integrated TDWR/LLWAS Alert System consisting of functional prototypes of both TDWR and LLWAS-3.

Alert terminology—In issuing an alert to a landing/departing pilot, the procedure called for Local Control to start by identifying it as either a "wind shear alert" or a "microburst alert." Wind shear alerts were of two kinds: (1) "gain" alerts (e.g., 20-kt gain 2-Mile Final), which were used to identify areas of increasing head winds associated with such wind shear features as gust fronts, and (2) "loss" alerts (e.g., 20-kt loss 2-Mile Final), which were used to identify areas of decreasing head winds associated with weak microbursts. Loss alerts for intensities of 30 knots or more were identified as microburst alerts to highlight the greater potential hazard.

SUMMARY AND CONCLUSIONS

1. ***The analysis covered at least 79 percent of the "alert" wind shears that occurred during the demonstration.*** The on-site demonstration team logged 130 wind shear features as possibly causing alerts to be issued to pilots landing and departing Orlando International Airport during the 65-day demonstration. The pilot-controller radio communication tapes were analyzed for 103 (or 79 percent) of the 130 wind shear features, which resulted in the analysis of 39 alert periods lasting a total of 10 hours.

2. ***Pilots received alerts from two systems during the demonstration:*** (1) TDWR-based alerts from May 4 though June 19, while the Integrated TDWR/LLWAS Alert Software Package underwent its pre-demonstration checkout, and (2) integrated alerts from June 20 through the end of the demonstration on July 7. The 39 examined alert periods includes periods when pilots received TDWR-based alerts and periods when pilots received integrated alerts.

3. ***Both alert systems used during the demonstration performed well*** in providing timely alerts of significant wind shear conditions. The 105 PIREPs received from landing and departing pilots during the 39 examined alert periods support this finding.

4. An examination of the alerts issued by Local Control identified two innovations being used by at least some of the controllers and one potential problem area.

   Innovation one: "adjacent-airspace-alert" advisories—One third of the alerts issued by Local Control did not affect the air crews directly but advised them of an alert in effect for some adjacent airspace. These situations primarily involved landing air crews being advised of an alert in effect for the airspace off the departure end of the arrival runway.

   RECOMMENDATION—The apparent use of "adjacent-airspace-alert" advisories as heads-up information for landing pilots in the event of a missed approach should be examined for possible inclusion into the formal guidelines to controllers on the issuance of alerts that will accompany the introduction of the operational system. Perhaps, these extra alerts could be issued on a "time-permitting" basis.

   Innovation two: use of non-standard phraseology—Controllers used non-standard phraseology in issuing three quarters of those alerts that located wind shear on the runway. Instead of using the standard phraseology of "over the runway" in those cases, the controllers substituted in the phrase "approach end of the runway" or "departure end of the runway" in an apparent attempt to provide more detailed location information.

   Potential problem area: "non-issued" alerts—Local Control did not issue 22 percent of the alerts called for during the 39 examined alert periods. These situations occurred at alert startup when Local Control did not issue the alert in effect to the first one or more air crews.

RECOMMENDATION—This number of "non-issued" alerts may warrant a re-examination of the means used to get controller attention at alert startup, a problem area identified in earlier demonstrations.

5. ***Trend is for increasing pilot utilization of alerts for microburst avoidance***–Relative to earlier demonstrations, more pilots used the issued alerts to avoid microburst encounters. For example, in the 1990 TDWR Demonstration at Orlando, a pilot landed/departed with a microburst alert in effect, on average, once every one to two days over the demonstration period. This average was reduced to one pilot every ten days during the 1992 Demonstration, representing a significant improvement in microburst avoidance.

6. ***One pilot that landed with a microburst alert in effect experienced difficulty***—The pilot, who had been issued a 30-knot microburst alert, advised Local Control after landing that nobody else should land to which the controller observed: "You sure beat that one by a whisker......just as you got to the other side of it, we had a microburst alert with a 60-knot loss on 3-Mile Final."

7. The following are the results of a "what if" comparison of four alert systems/softwares relative to what their operational impact would have been over the 39 examined alert periods:

    a. ***TDWR with 1990 software would have maximized alert activity***—TDWR with 1990 software, as a stand-alone alert system, would have maximized the alert activity during the demonstration with 13.5 hours of overall alert period duration and 233 air crews being issued an alert.

    b. ***The post-1990 software changes safely and significantly reduced TDWR alert activity***—The post-1990 TDWR software changes significantly reduced TDWR alert activity by: (1) 21 percent in terms of overall alert duration during the demonstration [from 13.5 to 10.7 hours], (2) 36 percent in terms of the number of air crews issued an alert [from 233 to 148 air crews], and (3) 68 percent in terms of the number of air crews issued a microburst alert [from 66 to 21 air crews]. An examination of the associated PIREPs suggests that the reduction in alert activity was justified.

    c. ***LLWAS would have minimized alert activity***—The LLWAS channel of the integrated TDWR/LLWAS system, as a stand-alone alert system, would have minimized the alert activity during the demonstration with 5.7 hours of overall alert period duration and 87 air crews being issued an alert. It should be noted that LLWAS alert coverage did not start until 2-Mile Final during the demonstration versus 3-Mile Final for TDWR, which, in part, explains the fewer alerts.

    d. ***TDWR/LLWAS integration into a single alert system would have provided a superior overall alert service***—The integration of TDWR and LLWAS into a single alert system has the potential to increase alert coverage, improve alert timeliness, decrease extraneous alerts, and improve alert accuracy relative to what either system can do alone. The demonstration provided examples in each of these areas. With integration, alert activity during the 39 examined alert periods would have been 10.5 hours in overall alert period duration and 141 air crews would have been issued an alert. This represents a slight decrease in alert activity over the TDWR channel alone and a sharp increase over the alert activity exhibited by the LLWAS channel alone.

8. ***Generalizing these operational results from Orlando to other airports is complicated***— Generalizing these results to other airports is complicated by the fact that the Orlando wind shear environment represents a relatively benign versus a worst-case demonstration site from an operational viewpoint. Relative to other airports, the Orlando, summer, wind shear environment is characterized by: (1) few gust fronts, and they tend to be weak; and (2) numerous microbursts, but the "wet" atmospheric conditions at Orlando allow pilots and controllers to associate/locate microbursts with rain shafts at the surface versus having to deal with them in "clear air."

ANALYSIS COVERED AT LEAST 79 PERCENT OF THE "ALERT" WIND SHEARS THAT OCCURRED DURING THE DEMONSTRATION

The on-site demonstration team maintained a log of all observed wind shear features that may have generated alerts at Orlando International Airport together with the maximum observed change in horizontal wind speed with distance observed for each of the features. Of the 130 wind shear features logged over the nine-week demonstration, 79 percent [or 103] have been included in the analysis. Specifically, the analysis includes: (1) 91 percent [or 86] of the 94 logged microbursts, which ranged in their maximum observed intensities from 20 to 70 knots, and (2) 47 percent [or 17] of the 36 logged gust fronts and sea breezes, which ranged in their maximum observed intensities from 15 to 25 knots.

The 103 wind shear events included in the analysis resulted in 39 alert periods that lasted a total of 612 minutes or slightly over 10 hours. The alert periods ranged in duration from less than 1 minute up to 38 minutes and averaged 15 minutes.

There is no formal definition as to what constitutes an alert period. For analysis purposes, an alert period was defined to start with the first alert generated for the airport and to end whenever alerts for the airport ceased to be generated for a period in excess of five minutes. Consequently, a startup of alerts in less than six minutes after they had ceased was considered to be a continuation of the original alert period.

WHAT HAPPENED OPERATIONALLY DURING THE 39 EXAMINED ALERT PERIODS

This section is concerned with the alerts issued to pilots by Local Control without taking into account their source (i.e., whether they were TDWR-based or integrated alerts). An analysis of the generated alerts by source is presented in the next section.

Runway Operations Ceased Many Times and for a Variety of Reasons

Either arrival runway operations or departure runway operations or both operations ceased for at least 5 minutes during 21 of the 39 alert periods examined. Operations ceased 23 times during these 21 alert periods for periods lasting up to 30 minutes and averaging 15 minutes in duration. Overall the operations ceased for 6 of the 10 hours that alerts were in effect. The communication tapes permitted at least some of the factors influencing the cessation of runway operations to be identified in each of the 23 cases.

> 8 of the 23 periods did not involve microburst alerts but involved such factors as: (1) pilot decisions not to land or take off due to the appearance of the weather in the vicinity of the airport and/or wind shear alerts being in effect, or (2) an Air Traffic management decision to shift runways or to restrict Orlando departures based on TRACON/ARTCC traffic management considerations.

15 of the 23 periods involved microburst alerts. Pilots declined to land or to take off and operations ceased on the impacted runway at or shortly after the startup of the microburst alerts. In some cases, operations ceased before microburst alert startup due to the factors listed above.

An Examination of the Alerts Issued by Local Control Identified Two Innovations and One Potential Problem Area

An examination of the alerts generated by the system and the alerts verbally issued by Local Control to landing/departing pilots indicates that 157 air crews did receive or should have received an alert:

- 25 of the 157 air crews were involved with situations where Local Control did not issue the alert in effect for the air crew. Almost all of these situations involved the first one or more air crews not being issued an alert after alert startup. This number of "non-issued" alerts may warrant a re-examination of the means used to get controller attention at alert startup, which was also identified as a problem area in earlier demonstrations.

- 41 of the 157 air crews were involved with situations where Local Control advised the air crew of an alert in effect for some adjacent airspace and primarily involved landing air crews being advised of an alert in effect for the airspace off the departure end of the arrival runway. The innovation of "adjacent-airspace-alert" advisories as heads-up information to pilots in the event of a missed approach appears to have been well received by the involved pilots and should be examined for possible inclusion into the formal guidelines to controllers on the issuance of alerts that will accompany the introduction of the operational system.

- 91 of the 157 air crews were involved with situations where Local Control issued the appropriate alert that was directly applicable to the airspace that was to be traversed during landing or takeoff.

The second innovation involved the 132 air crews that received either a "directly-applicable" alert or an "adjacent-airspace-alert" advisory and, specifically, the 61 air crews that received an alert/advisory that located the wind shear on the runway. In an apparent attempt to provide more detailed location information, controllers substituted in the phrase "approach end of the runway" or "departure end of the runway" in issuing 47 [or 77 percent] of the 61 alerts/advisories instead of using the standard phraseology "over the runway."

Pilot Utilization of Issued Alerts

Prior to the demonstration, some of the airlines operating out of Orlando were known to have instructed their pilots not to continue their landing or takeoff on receiving a microburst alert, if at all possible.

Table A-1 characterizes the "directly-applicable" alerts verbally issued to pilots during the 39 alert periods in terms of the intensity of the alert issued and the action taken by the pilot as to whether the landing/takeoff was completed or delayed. The table shows that: (1) few "gain" wind shear alerts were issued, as one would expect given the Orlando wind shear environment, and (2) few microburst alerts were issued directly to pilots, as one would expect given that runway operations ceased at microburst alert startup or shortly thereafter. Alert updates broadcast for status information during these operational pauses and not directed to specific aircraft actively in the process of landing or taking off were not included in the table. In terms of wind shear avoidance, 1 (or 12 percent) of the 8 air crews issued a "gain" wind shear alert

declined to land, 10 (or 14 percent) of the 70 air crews issued a "loss" wind shear alert declined to land or take off, and 7 (or 54 percent) of the 13 air crews explicitly issued a microburst alert declined to land or take off with the alert in effect.

Table A-1
Pilot Utilization of "Directly-Applicable" Alerts
Issued to Pilots During the 39 Examined Alert Periods

		Operational Outcome			
Alert Actually Issued to Pilot	Number of Air Crews Issued Such an Alert	Pilot Landed	Pilot Did Not Complete Landing	Pilot Took Off	Pilot Delayed Takeoff
+15kts	3	2	0	1	0
+20kts	3	1	1	1	0
+25kts	2	0	0	2	0
Higher	0	0	0	0	0
Subtotal	8	3	1	4	0
-15kts	12	7	0	4	1
-20kts	31	20	3	6	2
-25kts	27	14	2	9	2
Subtotal	70	41	5	19	5
-30kts	4	2	0	0	2
-35kts	6	1	1	2	2
-40kts	2	1	0	0	1
-45kts	0	0	0	0	0
-50kts	0	0	0	0	0
-55kts	1	0	1	0	0
Higher	0	0	0	0	0
Subtotal	13	4	2	2	5
TOTAL	91	48	8	25	10

Table A-2 shows the corresponding situation for the issued "adjacent-airspace-alert" advisories. It is seen that 6 of the 10 air crews issued a microburst alert advisory for a microburst in some adjacent airspace declined to land or take off.

Table A-2
Pilot Utilization of "Adjacent-Airspace-Alert" Advisories Issued to Pilots During the 39 Examined Alert Periods

		Operational Outcome			
Alert Actually Issued to Pilot	Number of Air Crews Issued Such an Alert	Pilot Landed	Pilot Did Not Complete Landing	Pilot Took Off	Pilot Delayed Takeoff
+15kts	0	0	0	0	0
+20kts	0	0	0	0	0
+25kts	0	0	0	0	0
Higher	0	0	0	0	0
Subtotal	**0**	**0**	**0**	**0**	**0**
-15kts	11	8	1	2	0
-20kts	12	8	0	4	0
-25kts	8	5	0	2	1
Subtotal	**31**	**21**	**1**	**8**	**1**
-30kts	1	1	0	0	0
-35kts	3	3	0	0	0
-40kts	5	0	1	0	4
-45kts	0	0	0	0	0
-50kts	0	0	0	0	0
-55kts	1	0	0	0	1
Higher	0	0	0	0	0
Subtotal	**10**	**4**	**1**	**0**	**5**
TOTAL	41	25	2	8	6

Table A-3 presents the operational details of the six air crews that proceeded to land or take off after receiving a "directly-applicable" microburst alert. It is seen from the table that four of air crews proceeded to land or take off into rapidly improving wind shear conditions that dropped to wind shear status within a minute of the microburst alert being issued to the air crew and that in one other case the microburst alert was a false alarm due to a faulty LLWAS sensor. In only one of these five cases was the air crew possibly notified of the improving/correct wind shear situation. This apparent ability to correctly evaluate the wind shear situation out the cockpit window is probably due to the Orlando wind shear environment which permits pilots to "see" microbursts in terms of blowing precipitation in close association with rain shafts.

However, one case makes the point that this out-the-window capability to correctly evaluate microburst situations is less than perfect among Orlando pilots. After landing, one pilot, who had been issued a 30-knot microburst alert, advised Local Control that nobody else should land to which the local controller observed: "You sure beat that one by a whisker......just as you got to the other side of it, we had a microburst alert with a 60-knot loss on 3-Mile Final."

Table A-3
Details of the Six Air Crews that Proceeded to Land or Take Off After Being Issued a Microburst Alert

Runway, Greenwich Mean Time, and Date of the Operation	Issued Alert	PIREP Content	Details of the Landing or Takeoff
1 Runway 36R Arrival at 1809 GMT on 6-15-92	40-knot loss 1-Mile Final	Smooth, ± 10 knots at 200 feet	This was the first approach to Runway 36R after a runway shift during the alert period. Wind shear conditions were improving rapidly on Runway 36R at the time in that alerts dropped to wind shear status [-25KTS/RWY] within a minute of the pilot receiving the microburst alert. The pilot was not advised of the status change directly but may have overheard the next pilot to contact Local Control for landing clearance receive a wind shear alert.
2 Runway 17 Arrival at 1646 GMT on 6-20-92	30-knot loss 2-Mile Final	No PIREP	This was the first alert issued to an air crew approaching Runway 17 during the alert period. Wind shear conditions were improving in that alerts dropped to wind shear status [-25KTS/2MF] one minute after the pilot received the microburst alert. Local Control did not advise the pilot of the change in status.

Table A-3
(Continued)

Runway, Greenwich Mean Time, and Date of the Operation	Issued Alert	PIREP Content	Details of the Landing or Takeoff
3 Runway 36R Departure at 1656 GMT on 6-20-92	35-knot loss Departure End	No PIREP	This was the first departure from Runway 36R after a runway shift during the alert period. Wind shear conditions were improving rapidly on Runway 36R in that alerts dropped to wind shear status [-20KTS/RWY] one minute after the pilot received the microburst alert. In addition, the pilot turned sharply after takeoff in order to avoid the rain shaft at the departure end of the runway. Controller and pilots commonly use rain shafts as markers to locate microbursts at Orlando International Airport.
4 Runway 18R Arrival at 1837 GMT on 6-23-92	35-knot loss over runway	No PIREP	This was a false alert caused by a bad LLWAS sensor as noted in the daily log maintained by the on-site demonstration team. The LLWAS channel was temporarily taken out of service shortly after this aircraft landed.
5 Runway 17 Departure at 2119 GMT on 7-06-92	35-knot loss Departure End	No PIREP	This was the first departure from Runway 17 after departure operations had ceased for 8 minutes due to microburst alerts being in effect and other thunderstorm activity in departure airspace. Wind shear conditions were improving rapidly at the time on Runway 17 in that alerts dropped to wind shear status [-25KTS/RWY] within a minute of the pilot receiving the microburst alert. In addition, the pilot turned sharply after takeoff in order to avoid the rain shaft and associated wind shear at the end of the departure end of the runway.
6 Runway 17 Arrival at 2044 GMT on 7-07-92	25-knot loss 3-Mile Final Updated to 30-knot loss 3-Mile Final 85 sec. later	Advise nobody land on 17	The alert period started seconds before this pilot requested landing clearance. Wind shear conditions were worsening rapidly during the approach as evidenced by the two alerts issued to the pilot and the comment made by Local Control to the pilot shortly after landing "You sure beat that one by a whisker...just as you got to the other side of it, we had a microburst alert with a 60-knot loss at 3-Mile Final." Arrival operations ceased after this landing.

In contrast to earlier demonstrations, this demonstration suggests that more pilots are seeking to avoid microburst encounters. For example, during the 1990 Orlando TDWR Demonstration pilots took off or landed after being issued a microburst alert once every one to two days, on average [i.e., 29 air crews did so over the 37-day demonstration]. However, during the 1992 Demonstration, this average was reduced to roughly once every ten days [i.e., six air crews landed or took off after being issued a microburst alert over the 65-day demonstration].

Pilot use of issued alerts for microburst avoidance is key if the envisioned safety benefit is to be realized by the deployed system. The 1992 Demonstration suggests a trend that favors the future realization of the system's envisioned safety benefit.

System Performed Well Overall Based on Pilot Reports

PIREPs of the wind and weather conditions observed/experienced by pilots were received from 31 of the 91 air crews that received a "directly-applicable" alert and from an additional 74 landing/departing air crews during the 39 examined alert periods. Based on these 105 PIREPs, the system, overall, provided landing/departing pilots with timely alert coverage of all significant wind shear conditions.

TDWR and the Integrated TDWR/LLWAS alert systems were not designed to provide alert coverage for all wind-related encounters experienced by landing/departing pilots. Table A-4 characterizes the four encounters not provided alert coverage during the 39 examined alert periods. A review of the Doppler and mesonet data indicated that the encounters involved two wind conditions not provided alert coverage: (1) thermals, and (2) periods of strong, gusty surface winds that are not in close association with an area of organized with shear (e.g., a gust front or microburst).

Table A-4
Four Encounters Reported by Pilots that Were Not Provided Alert Coverage by the Tested System During the 39 Examined Alert Periods

Runway, Greenwich Mean Time and Date of the Operation (1) (2)	PIREP Content	"Best Guess" Explanation as to Why Alert Coverage Was Not Provided In This Case (3)
1 Pilot landed on Runway 17 at 1551 GMT on 6-05-92	Winds are real strong... the following pilot may want to go around	A review of the Doppler data suggests that the aircraft encountered strong, turbulent, surface cross winds associated with a macroburst's outflow. The airport's centerfield wind at the time of the encounter was 240 degrees at 15 knots, gusting to 40 knots. The system did not generate alerts in this case because a microburst was not involved and the outer edge of the outflow did not trigger gust-front-based alerts for it was delineated by a broad area of slowly increasing wind speeds rather than by the narrow band of sharply increasing wind speeds [i.e., wind shear] that typically defines a gust front.
2 Pilot landed on Runway 18R at 2220 GMT on 6-20-92	Pretty good sinker at 800 feet	A review of the Doppler data suggests that this and the next aircraft encountered a weak gust front outflow from a distant microburst, <u>not an apparent alert situation</u>.
3 Pilot landed on Runway 18R at 2222 GMT on 6-20-92	Gained 15 to 20 knots at 800 feet	See the above entry.
4 Pilot took off from Runway 18L at 2244 GMT on 6-30-92	Lost 15 to 20 knots at 1000 feet	Nothing was seen in the Doppler data suggesting that the aircraft encountered some sort of small-scale, wind shear feature [e.g., a thermal], <u>not an alert situation</u>.

Note: (1) Results are based on a review of the 39 examined alert periods for those pilots for which an alert was not generated yet reported a relatively intense encounter (i.e., an airspeed variation in excess of 15 knots, moderate or greater turbulence, any indication of a downflow, or any suggestion that extra caution was advisable).
(2) The Greenwich Mean Time (GMT) refers to the time that Local Control issued landing/takeoff clearance to the pilot.
(3) These explanations are based on discussions with Lincoln Laboratory personnel who had access to the stored Doppler weather radar and Mesonet data for the pertinent periods.

A "WHAT IF" COMPARISON OF FOUR ALERT STRATEGIES RELATIVE TO THEIR IMPACT OVER THE 39 EXAMINED ALERT PERIODS

Four alert systems/softwares were examined relative to what their operational impact would have been over the 39 examined alert periods: (1) the Integrated TDWR/LLWAS System, (2) the TDWR channel of the Integrated System as a stand-alone alert system, (3) the LLWAS channel as a stand-alone alert system, and (4) TDWR as a stand-alone alert system but using the alert software as it existed in 1990. Table A-5 compares the four alternatives in terms of the overall system alert activity that would have occurred. The left side of the table compares the two versions of TDWR as stand-alone alert systems to the Integrated TDWR/LLWAS system and shows an overall decrease in alert activity. The right side of the table compares LLWAS as a stand-alone alert system to the Integrated TDWR/LLWAS system and shows an overall increase in alert activity.

The earliest form of the alert systems/softwares examined was TDWR as a stand-alone system using 1990 alert software. Major modifications were made to the TDWR software after 1990 to reduce the extent that "nuisance" alerts occurred and to improve the overall accuracy of the alerts issued to pilots. It is seen from Table A-5 that this alternative would have maximized alert activity during the 1992 Demonstration in terms of the amount of time that the runways were under alert status at 808 minutes or 13.5 hours and the number of air crews issued an alert at 233 air crews.

The second alternative was TDWR as a stand-alone alert system using 1992 software. In the 1992 Demonstration, use of TDWR as a stand-alone alert system with 1992 versus 1990 software would have reduced alert activity by: (1) 21 percent in terms of overall alert duration [10.7 versus 13.5 hours], (2) 36 percent in terms of the number of air crews for which an alert was generated [148 versus 233 air crews], and (3) 68 percent in terms of the number of air crews for which a microburst alert was generated [21 versus 66 air crews].

PIREPs support the reduction in alert activity in that the worst-case encounter reported by those pilots that would have received: (1) an alert with the 1990 software but not with the 1992 software was for a "15-knot gain," a threshold-level encounter, or (2) a microburst alert with the 1990 software but a "loss" wind shear alert with the 1992 software was for a "20-knot gain," a less-than-microburst-intensity encounter.

The third alternative was the LLWAS channel of the integrated TDWR/LLWAS alert system as a stand-alone alert system using 1992 software. It is seen from Table A-5 that this alternative would have minimized alert activity during the 1992 Demonstration in terms of the overall amount of time that the runways were under alert status at 5.7 hours and the number of operations issued an alert at 87 air crews. This "minimum" finding may not be representative of airports with a high ratio of gust fronts to microbursts relative to Orlando's wind shear environment, such as at Denver's Stapleton International Airport.

Table A-5
Alert System/Software Comparison Relative to Alert Activity

Alert Activity	1990 TDWR Alert Software	1992 TDWR Alert Software	1992 Integrated TDWR/LLWAS Alert Software	1992 LLWAS Alert Software	1992 Integrated TDWR/LLWAS Alert Software
<u>Alert Periods</u>					
Number	39 alert periods	37	40	33	40
Duration					
Total	808 minutes	640	628	342	628
Range	2 to 68 mins.	1 to 42	1 to 37	1 to 31	1 to 37
Average/ period	20 mins./period	17	15	10	15
Average/ week	90 mins./week	71	70	38	70
<u>Number of Air Crews That Would Have Received an Alert</u>					
Total Number	233 air crews	148	141	87	141
Microburst Alert	66 air crews	21	21	14	21
"Loss" Wind Shear Alert	141 air crews	101	92	40	92
"Gain" Wind Shear Alert	26 air crews	26	28	33	28

The fourth and final alternative was the integrated TDWR/LLWAS alert system using the 1992 software. Tables A-6 and A-7 present the impact of integration over what the individual TDWR and LLWAS channels would have done as stand-alone alert systems over the 39 examined alert periods. From the tables, one sees the extent that integration increased alert coverage, improved alert timeliness, decreased extraneous alerts, and improved alert accuracy relative to what either TDWR or LLWAS would have done alone.

Table A-6
Impact of TDWR/LLWAS Integration on Alerts Generated by the TDWR Channel

Envisioned Impact of Integration on TDWR-based Alerts	The "What If" Results Relative to the 39 Examined Alert Periods
1. Reduction in potential nuisance alerts [i.e., elimination of all "gain" wind shear alerts and 15-knot "loss" wind shear alerts not confirmed by the LLWAS channel]	34 air crews that would have received a TDWR-based alert would not have received an integrated alert...the PIREPs support the elimination of these alerts in that the most intense encounter reported by this group was for a "10-knot gain last 400 feet," a non-alert situation.
2. More accurate alerts involving gust fronts, microbursts and outflows that could intensify to microburst alert status	23 air crews that would have received a TDWR-based alert would also have received an integrated alert but with some difference in terms of the wind shear intensity and/or location estimates...the PIREPs only provided sufficient detail in one case for a comparison and that case supports the downgrading of a TDWR-based, microburst alert to an integrated, "loss" wind shear alert. The PIREP was for "10-knot gain, then a 12-knot loss and strong lateral winds."
3. Expanded alert coverage of gust fronts	20 air crews that would not have received a TDWR-based alert would have received an integrated, "gain" wind shear alert...the PIREPs tend to support the integrated alerts [i.e., "gained 20 knots on Short Final" and "30-knot tail wind, going around"] but there were also four PIREPs indicating something to the effect that "little or nothing was encountered."
4. Expanded alert coverage of outflows that could intensify to microburst alert status	7 air crews that would not have received a TDWR-based alert would have received an integrated, "loss" wind shear alert...the sole PIREP received from this group does not support the integrated alerts in this case in that the pilot reported "no change in airspeed."
5. More timely alerts	1 air crew would have received a more timely integrated alert in the form of a "gain" wind shear alert versus a later TDWR-based alert....the PIREP received from this pilot supports the integrated alert, "gained 12 to 15 knots at 450 feet."
6. A resulting change in overall alert activity	2% decrease in overall alert duration [10.5 versus 10.7 hours] and a 5% decrease in terms of the number of air crews issued an alert [141 versus 148 air crews]. These modest decreases reflect the low ratio of gust fronts to microbursts impacting Orlando International Airport.

Table A-7
Impact of TDWR/LLWAS Integration on Alerts Generated by the LLWAS Channel

Envisioned Impact of Integration on LLWAS-based Alerts	The "What If" Results Relative to the 39 Examined Alert Periods
1. Expanded alert coverage of microbursts and outflows that could intensify to microburst alert status.	63 air crews that would not have received an LLWAS-based alert would have received an integrated "loss" wind shear alert [59 air crews] or a microburst alert [4 air crews]...PIREP support is mixed for the integrated alerts from these air crews [i.e., 3 air crews reported significant encounters, such as "gained 20 knots," versus 12 air crews that reported something to the effect that "little or nothing was encountered"]. The mixed PIREP support might reflect the wet atmospheric conditions at Orlando that permit pilots to frequently use rain shafts as markers to locate microbursts in making their go/no-go landing and takeoff decisions. Note that 12 of the 63 air crews chose either to delay their takeoff or to go around.
2. More accurate alerts involving microbursts and outflows that could intensify to microburst alert status.	33 air crews that would have received an LLWAS-based alert would also have received an integrated alert but with some difference in terms of the: (a) wind shear intensity estimate, (b) wind shear location estimate, and/or (c) the type of wind shear involved...the PIREPs do not provide sufficient detail for an evaluation of the differences between the LLWAS-based and integrated alerts.
3. More timely alerts involving microbursts and outflows that could intensify to microburst alert status.	11 air crews would have received a more timely integrated alert in the form of a "loss" wind shear alert [6 air crews] or a microburst alert [5 air crews] versus a later LLWAS-based alert...pilot actions and PIREPs support the integrated alerts in that 5 air crews [3 issued a microburst alert and 2 issued a "loss" wind shear alert] chose to either delay takeoff or to go around and two pilots landed and reported "advise that nobody land" and "shear at 300 feet."
4. Reduction in potential nuisance alerts [i.e., elimination of 15-knot "loss" wind shear alerts not confirmed by the TDWR channel].	9 air crews that would have received a 15-knot, LLWAS-based alert would not have received an integrated alert...the sole PIREP from this group supports the elimination of these alerts, "no airspeed variation, smooth ride."
5. A resulting change in overall alert activity.	84% increase observed in terms of overall alert duration [10.5 versus 5.7 hours] and a 62% increase observed in terms of the number of air crews that would have been issued an alert [141 versus 87 air crews]. These increases reflect the high ratio of microbursts to gust fronts impacting Orlando International Airport.

One also finds in the tables that the PIREPs tend to support the extensive changes introduced by integration overall but that the support is modest to nonexistent in certain instances. It is suggested that this is due to two factors related specifically to Orlando and the 1992 Demonstration: (1) Orlando pilots experience and report few significant wind shear encounters relative to other airports, such as Stapleton International Airport, because the pilots tend to be skilled at using the visual cues available in the wet, Orlando environment to "see" and avoid microbursts and outflows that could increase to microburst alert status, and (2) the 1992 Demonstration provided surprisingly few PIREPs overall with which to evaluate the alternative alert systems/softwares.

LOST PIREPs

It is clear from the communication tape analysis done for this study that the taping method used during the demonstration did not record all the PIREPs provided by landing pilots. The taping was done at the TDWR site, which was located some miles from the airport. Apparently, there were line-of-sight problems between the radio antenna at the radar site and portions of the airport's runways and taxiways. At times throughout the demonstration, Local Control could be heard on the communication tapes requesting PIREPs from pilots that had just landed, but no replies could be heard except for the pilot keying the microphone in making a response. Based on listening to the tapes, it is believed that a substantial number of PIREPs were lost during the 1992 Demonstration.

If communication tapes are to be saved for possible analysis during future demonstrations, the issue of "lost PIREPs" due to off-airport taping of Local Control-pilot radio communications should be addressed.